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Experimental study of the wave-dissipating performance of a four-layer horizontal porous-plate breakwater

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ABSTRACT

This paper proposes a four-layer submerged horizontal porous plate breakwater to improve the wave-dissipation efficiency under a wide range of incident wave frequencies, especially long incident waves, and also discusses the design of the geometrical parameters, i.e., plate submergence and porosity. The breakwater performance was examined experimentally in a two-dimensional wave flume. The effects of the layer number, breakwater width, upper plate porosity, and incident wave height were compared. Increasing the layer number and breakwater width or reducing the upper plate porosity can be favorable to energy dissipation for long incident waves. A moderate alteration of the submerged depth of each layer shifts the proportion of energy reflected or transmitted but minimally affects the energy-dissipation performance. In addition, the incident wave height affects both energy dissipation and mass overtopping, and the combined effect is related to the incident wave frequency and steepness. Generally, the proposed four-layer breakwater demonstrates satisfactory performance under a wide range of incident wavelengths and has promising future applications in coastal engineering. An optimized design for the plate porosity and submergence can be expected to further improve the breakwater performance, and a detailed mechanism for non-linear wave interactions with the submerged horizontal porous plate warrants further study.

1. Introduction

As an economical and ecologically friendly wave-dissipation and coastal-protection structure, the horizontal porous plate breakwater offers advantages over those of caisson, rubble mound and vertical wall types (Yu, 2002; Liu et al., 2008). In contrast to conventional bottom mounded breakwaters, a horizontal-plate breakwater type can be designed as floating or pile-supported type, which is less dependent on bad sea conditions and water depths. Furthermore, horizontal plates can avoid heavy horizontal wave force impacting on the structure, and the porosity further reduces the vertical force and attenuates additional wave energy. However, the wave-dissipating performance of the horizontal-plate type breakwater is largely influenced by its submergence and geometry parameters (i.e., plate width and porosity). Therefore, research on wave interaction with horizontal porous plates is needed to predict the performance and optimize the design for engineering applications.

The submerged horizontal plate was proposed as a breakwater in the 1970s (Hattori, 1975; Siew and Hurley, 1977; Hattori and Matsumoto, 1977), and since then, its characteristics (i.e., coefficients of wave reflection, transmission, energy dissipation and vertical force) related to variations of plate width, submerged depth, and incident wavelength have been widely investigated. Several early investigations into the fully submerged solid horizontal plate (e.g., the maximal reflection and the minimal transmission problem by Patarapanich (1984) and Patarapanich and Cheong (1989), the effect of moorings on the total reflection and total transmission coefficients of a moored horizontal plate by McIver (1985), and the ability to reflect short incident waves by Liu and Iskandarani (1991)) revealed several limitations of the horizontal solid plate when used as a breakwater. The solid plate has little to no effect on attenuation of wave energy, mostly by breaking scattered waves over the plate and inducing vortices at the plate tips (see, e.g., Dick and Brebner, 1969; Patarapanich and Cheong, 1989; Yu et al., 1995; Brossard and Chagdali, 2001). Incident waves in a specific frequency band, which is usually relatively narrow, can be blocked and reflected, and waves that propagate into the lee side might cause resonance in the sheltered area and degrade sailing conditions. Therefore, a breakwater with porous plates was proposed, and its wave-dissipating performance is enhanced

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by porosity-induced vortices (Yu and Chwang, 1994; Chwang and Wu, 1994; Yip and Chwang, 1998). Yu and Chwang (1994) suggested that the proper porosity could maintain the wave transmission at a low level while suppressing the wave reflection and the vertical force on the plate, and an investigation into the wave interaction with a periodic pitching porous plate by Yip and Chwang (1998) indicated a similar conclusion. Cho and Kim (2000) considered the hydroelastic effect of a horizontal porous flexible membrane on wave-blocking performance under monochromatic incident waves. For a membrane of relatively small width, greater flexibility leads to better wave-blocking performance, whereas for a relatively wide membrane, increasing the flexibility worsen the performance except under notably long and short waves. In addition, the study also indicated that a membrane of larger size does not necessarily produce better performance. The wave-dissipating performance of a submerged inclined plate breakwater was investigated analytically by Cho and Kim (2008) and examined experimentally by Rao et al. (2009). A porous plate of the proper inclination angle near the free surface is favorable to performance. Cho and Kim (2013) investigated the interaction of oblique monochromatic incident waves with a submerged horizontal porous plate and indicated that a plate porosity value near 0.1 and a submerged depth near $0.05h \sim 0.1h$ might be optimal for the performance, where h is the water depth.

Nonetheless, only one layer of the submerged plate might not create sufficient efficiency under large variations of the tidal level or a wide range of incident wave frequencies. The twin-plate breakwater, which consists of a horizontal surface plate and a submerged plate located immediately below the surface plate, was investigated analytically by Usha and Gayathri (2005) and experimentally by Neelamani and Gayathri (2006). Although wave transmission can be greatly reduced by the breakwater with a surface plate, the wave reflection is quite significant. Additionally, Liu et al. (2008) analytically examined a double-layer submerged horizontal plate breakwater with an upper porous plate and a lower solid plate and indicated that the proper porosity of the upper plate can aid in suppressing the vertical force on both layers at a relatively low level, and the efficiency could be further enhanced by making the lower plate permeable as well. More recently, wave interaction with double-layer submerged horizontal porous plates was investigated by Cho et al. (2013) and Liu and Li (2014), based on both numerical solutions and experimental results, and the effect of plate submergence and porosity was discussed. The results from Cho et al. (2013) indicated that the contribution of the lower plate to wave dissipation might be weakened if the spacing between the two plates exceeds 10% of the water depth. This result implied that a limitation of the covered water depth exists for a double-layer horizontal plate breakwater and its efficiency in dissipating long incident waves, the energy of which propagate more deeply. Therefore, one solution is to increase the layer number. A breakwater that consists of a stack of horizontal solid plates has been proposed (Wang and Shen, 1999; Wang et al., 2006). Wang and Shen (1999) suggested that the spacing between layers should be relatively small to improve the multi-layer breakwater's performance, and the related experimental study conducted by Wang et al. (2006) demonstrated that the upright wave force acting on the solid plate is relatively strong. However, investigations into the wave-dissipating performance of a multi-layer submerged horizontal porous plate breakwater are not yet found in the published literature.

This paper proposes a four-layer submerged horizontal porous plate breakwater. The addition of the lower two plates is intended to improve the performance under long incident waves. With properly designed plate porosity, improvement in wave dissipation can be achieved while suppressing the vertical wave force. The performance of the proposed breakwater was examined using physical model tests in a two-dimensional wave flume. The following section discusses the design of the geometrical parameters (i.e., submergence and porosity of plates). The third section describes the experiment setup and the details of test cases. The experimental results of specific characteristics (i.e., the effect of layer number, plate width, porosity, and submergence) are shown and discussed thereafter. The final section illustrates the conclusions.

2. Design of the breakwater

The horizontal porous plate plays a role in attenuating the incident wave energy by obstructing the vertical motion of fluid particles, inducing vortices, and breaking scattered waves over the plate. The vertical velocity distribution of fluid particles makes a significant difference in the wave-dissipation efficiency. Hence, the fluid velocity distribution should be taken into consideration in breakwater design.

Considering the inviscid and incompressible water and irrotational flow in a two-dimensional domain xoz of which the origin is set on the free surface, the velocity potential ϕ of the monochromatic propagating wave can be written as Eq. (1) based on the linear wave theory:

$$\phi = \frac{gA}{\omega}\frac{\cosh k(z+h)}{\cosh(kh)}\sin(kx-\omega t), \tag{1}$$

where g is the gravitational acceleration, A is the incident wave amplitude, h is the constant water depth, ω and k denote the incident wave frequency and wave number, respectively, x and z are spatial coordinates, and t is time. The velocity amplitude of fluid particles along the submerged depth can be described as:

$$U = \frac{Agk}{\omega}\frac{\cosh k(z+h)}{\cosh(kh)}, \tag{2}$$

$$V = \frac{Agk}{\omega}\frac{\sinh k(z+h)}{\cosh(kh)}, \tag{3}$$

where U and V denote the amplitudes of the horizontal and vertical velocity, respectively. Figure 1 shows the variation of vertical velocity component with submerged depth under four different incident wave numbers (the dimensionless wave numbers $kh = 1.0 \sim 8.0$) in which the vertical velocity is normalized by that on the free surface $V|_{z=0}$. The vertical velocity drops swiftly as the submerged depth increases under relatively short incident waves, whereas under longer incident waves, relatively significant amplitudes can be maintained in deeper water. A relatively small submergence of the upper plate and spacing between the upper and the second plates are favorable to the breakwater's efficiency. However, submerged depths of these two plates that are too small might

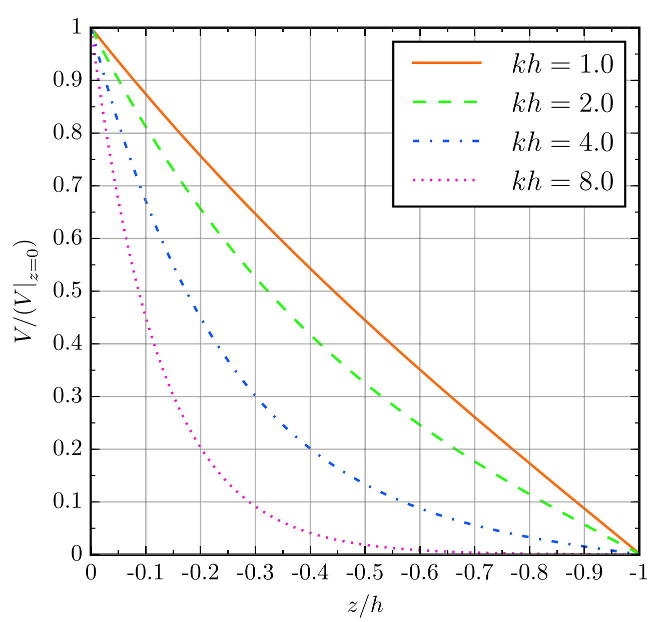

Fig. 1. Vertical velocity of fluid particles along the submerged depth.